Journal of ELECTRICAL ENGINEERING, VOL. 54, NO. 1-2, 2003, 46–51

A NEW DECOUPLING CONTROL SCHEME FOR THE PARALLEL OPERATION OF UPS

Lin Xinchun — Duan Shanxu — Kang Yong — Chen Jian *

This paper presents a new decoupling control scheme for paralleling UPS. The proposed control scheme can effectively weaken the coupling between the variable regulating frequency and the voltage amplitude (or between the variable regulating voltage amplitude and phase) As a result, it can avoid the positive feedback and improve the performance of dynamic response. The simulation and experimental results show that the proposed control scheme can not only achieve good dynamic performance but also improve stability.

K e y w o r d s: UPS, active power, reactive power, decoupling control, parallel operation, circulating current

1 INTRODUCTION

Uninterruptible Power Supplies (UPS) are used to provide the power to critical loads such as computers, satellite systems, bank transactions, and life support equipment. In order to improve the reliability of the whole system, the demand for the UPS system connected in parallel is increasing [1], [2]. The parallel operation of UPS has many desirable features such as expandability of output power, ease of maintenance, and redundancy implementation.

Now there are many control schemes of paralleling UPS [3], [4], however, regulating the phase (or frequency) with active power while regulating the voltage amplitude with reactive power are more appreciated [5], [6], because this control scheme can achieve good active and reactive power sharing between paralleled UPS in static state. However, we can see in Section 2.2 that this traditional control scheme may introduce positive feedback during the process of regulating phase (or frequency) and amplitude. As a result, it may lead to the oscillation or even instability of the whole system.

In this paper, we propose a new decoupling control scheme to overcome the problems caused by the traditional control scheme. In this new control scheme, the phase (or frequency) is regulated by a new control variable instead of active power, while the voltage amplitude is regulated by another new variable instead of reactive power. In order to validate the decoupling control scheme, we give the simulation and experimental results for the parallel operation of two single-phase UPS with no control interconnection. The simulation and experimental results prove that the new decoupling control scheme can achieve better performance of dynamic response, and, at the same time, the proposed control scheme can avoid oscillation and instability of the UPS paralleling system.

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2 LIMITATION OF THE TRADITIONAL CONTROL SCHEME

To simplify the analysis, the equivalent circuit of two single-phase paralleled UPS is shown in Fig. 1, where $E_1\angle\theta_1$ and $E_1\angle\theta_1$ are the output voltages of UPS1 and UPS2, I_1 and I_2 are the output currents of UPS1 and UPS2, jX and r_L are the line reactance and line resistance, respectively, $\dot{V}$ is the load voltage, R is the load resistance.

2.1 Calculation of active and reactive power

Using the instantaneous power theory [7], we can calculate the instantaneous output active and reactive powers of UPS1 and UPS2 from Fig. 1 as follows,

$$P_1 = \frac{1}{R(r_L^2+X^2)\left[(2+r_L/R)^2+(X/R)^2\right]}\Big\{ -E_1^2\left(2r_LR+r_L^2-X^2\right)+E_1^2r_LR\left[(2+r_L/R)^2+(X/R)^2\right] - E_1E_2(2r_LR+r_L^2-X^2)\cos(\theta_1-\theta_2) + 2E_1E_2X(R+r_L)\sin(\theta_1-\theta_2)\Big\} \tag{1}$$

$$P_2 = \frac{1}{R(r_L^2+X^2)\left[(2+r_L/R)^2+(X/R)^2\right]}\Big\{ -E_2^2\left(2r_LR+r_L^2-X^2\right)+E_2^2r_LR\left[(2+r_L/R)^2+(X/R)^2\right] - E_1E_2(2r_LR+r_L^2-X^2)\cos(\theta_2-\theta_1) + 2E_1E_2X(R+r_L)\sin(\theta_2-\theta_1)\Big\} \tag{2}$$

$$Q_1 = \frac{1}{R(r_L^2+X^2)\left[(2+r_L/R)^2+(X/R)^2\right]}\Big\{ -E_1^2X\left\{(2R+2r_L-R\left[(2+r_L/R)^2+(X/R)^2\right]\right\} - 2E_1E_2(r_L+R)X\cos(\theta_1-\theta_2) - E_1E_2(2r_LR+r_L^2-X^2)\sin(\theta_1-\theta_2)\Big\} \tag{3}$$

$$Q_2 = \frac{1}{R(r_L^2+X^2)\left[(2+r_L/R)^2+(X/R)^2\right]}\Big\{ -E_2^2X\left\{(2R+2r_L-R\left[(2+r_L/R)^2+(X/R)^2\right]\right\} - 2E_1E_2(r_L+R)X\cos(\theta_2-\theta_1) - E_1E_2(2r_LR+r_L^2-X^2)\sin(\theta_2-\theta_1)\Big\} \tag{4}$$

where P_1 and P_2 are the output active powers of UPS1 and UPS2, respectively, while Q_1 and Q_2 are the output reactive powers of UPS1 and UPS2.

2.2 Limitation of the traditional control scheme

In the traditional control scheme, the phase (or frequency) is controlled by the error of active powers, while the amplitude is controlled by the error of reactive powers. For the convenience of analysis, we will only point out the limitation of regulating phase (or frequency) with active power, and the limitation of regulating voltage amplitude with reactive power can be analyzed in the same way. If $P_1 > P_2$, then $Q_1 < Q_2$ holds in static state under the traditional control scheme. So the assumption is defaulted in the traditional control scheme that $P_1 > P_2$ is caused only by $Q_1 > Q_2$, and independent of E_1 and E_2. However, from equations (1) and (2) we can see that P_1 and P_2 are related not only with θ_1 and θ_2, but also with E_1 and E_2. As a result, maybe $P_1 > P_2$ is satisfied in the situation of $\theta_1 < \theta_2$. So regulating the phase (or frequency) with the error of active powers may introduce the positive feedback, which will lead to oscillation or instability of the whole system.

2.3 Limiting range for the traditional control scheme

From the analysis in Section 2.2, we can see that the traditional control scheme may lead to positive feedback, we will give the condition for positive feedback in the following.

The errors of active and reactive powers can be obtained from equation (1), (2), (3), and (4) as follows

$$\Delta P = P_1 - P_2 = \frac{1}{R(r_L^2+X^2)\left[(2+r_L/R)^2+(X/R)^2\right]}\Big\{ -(E_1^2-E_2^2)\left(2r_LR+r_L^2-X^2\right)+(E_1^2-E_2^2)r_LR\big[(2+r_L/R)^2 + (X/R)^2\big] + 4E_1E_2X(r_L+R)\sin(\theta_1-\theta_2)\Big\} \tag{5}$$

$$\Delta Q = Q_1 - Q_2 = \frac{1}{R(r_L^2+X^2)\left[(2+r_L/R)^2+(X/R)^2\right]}\Big\{ (E_1^2-E_2^2)RX\left[(2+r_L/R)^2+(X/R)^2\right] - 2(E_1^2-E_2^2)(r_L + R)X - 2E_1E_2(2r_LR+r_L^2-X^2)\sin(\theta_1-\theta_2)\Big\} \tag{6}$$

similarly, regulating phase (or frequency) with the error of active powers will be analyzed in the following. If $\theta_1 > \theta_2$, then the limiting range is referred to the possible values of θ_1, θ_2 and E_1, E_2 while meeting $\Delta P = P_1 - P_2 < 0$. For example, if $E_2 = 140$ V, $R = 5\,\Omega$, $r_L = 0.3\,\Omega$, $X = 0.314\,\Omega$, $\theta_2 = 0$, $E_1 = 80$ V, then $0 < \theta_1 < 36.755°$ is the limiting range for the traditional control scheme. In other words, when $0 < \theta_1 < 36.755°$, then the traditional control scheme may introduce positive feedback, which will lead to oscillation or instability.

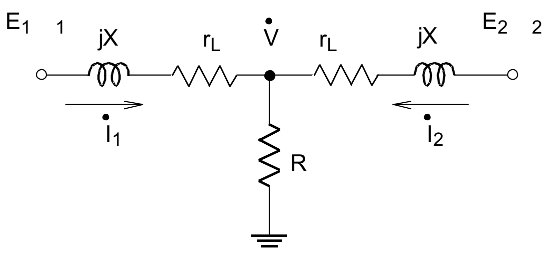

Fig. 1. Equivalent circuit of two paralleled UPS

3 THE PROPOSED DECOUPLING CONTROL SCHEME

3.1 The calculation of decoupling parameters

$\theta_1 > \theta_2$ (or $E_1 > E_2$) unnecessarily leads to $P_1 > P_2$ (or $Q_1 > Q_2$) is the limitation of the traditional control scheme, which can be seen from the analysis above. If we can find new control variables TP_1, TP_2, TQ_1, and TQ_2,(TP_1 and TP_2 are variables regulating the phase or frequency, while TQ_1, and TQ_2 are variables regulating the voltage magnitude), which meet $TP_1 > TP_2$ (or $TQ_1 > TQ_2$) when $\theta_1 > \theta_2$ (or $E_1 > E_2$) is satisfied, and at the same time, the active and reactive powers sharing in static state must be ensured using TP_1, TP_2, TQ_1, and TQ_2 as the new control variables, then we can overcome the limitation of the traditional control scheme by adopting TP_1, TP_2, TQ_1, and TQ_2 as the new control variables.

Basing on this, suppose that the expressions of TP_1, TP_2, TQ_1, and TQ_2 are,

$$\begin{aligned} TP_1 &= K_{11}P_1 + K_{12}Q_1 \\ TQ_1 &= K_{21}P_1 + K_{22}Q_1 \end{aligned} \tag{7}$$

$$\begin{aligned} TP_2 &= K_{11}P_2 + K_{12}Q_2 \\ TQ_2 &= K_{21}P_2 + K_{22}Q_2 \end{aligned} \tag{8}$$

then,

$$\begin{aligned} &TP_1 - TP_2 = K_{11}(P_1 - P_2) + K_{12}(Q_1 - Q_2) = K_{11}\Delta P \\ &+ K_{12}\Delta Q = \frac{1}{R(r_L^2 + X^2)\left[(2+r_L/R)^2 + (X/R)^2\right]}\Big\{-(E_1^2 \\ &- E_2^2)(2r_LR + r_L^2 - X^2)K_{11} + (E_1^2 - E_2^2)\big\{R\big[(2+r_L/R)^2 \\ &+ (X/R)^2\big](r_LK_{11} + XK_{12}) - 2X(R + r_L)K_{12}\big\} \\ &+ \sin(\theta_1 - \theta_2)E_1E_2\big[4X(r_L + R)(K_{11} \\ &- 2(2r_LR + r_L^2 - X^2)K_{12}\big]\Big\} \end{aligned} \tag{9}$$

$$\begin{aligned} &TQ_1 - TQ_2 = K_{21}(P_1 - P_2) + K_{22}(Q_1 - Q_2) = K_{21}\Delta P \\ &+ K_{22}\Delta Q = \frac{1}{R(r_L^2 + X^2)\left[(2+r_L/R)^2 + (X/R)^2\right]}\Big\{-(E_1^2 \\ &- E_2^2)(2r_LR + r_L^2 - X^2)K_{21} + (E_1^2 - E_2^2)\big\{R\big[(2+r_L/R)^2 \\ &+ (X/R)^2\big](r_LK_{21} + XK_{22}) - 2X(R + r_L)K_{12}\big\} \\ &+ \sin(\theta_1 - \theta_2)E_1E_2\big[4X(r_L + R)(K_{21} \\ &- 2(2r_LR + r_L^2 - X^2)K_{22}\big]\Big\}. \end{aligned} \tag{10}$$

Obviously, if formulas (11), (12), (13), and (14) are satisfied, then $\theta_1 > \theta_2$ (or $E_1 > E_2$) will lead to $TP_1 > TP_2$ ($TQ_1 > TQ_2$).

$$\begin{aligned} &R\left[(2+r_L/R)^2 + (X/R)^2\right](r_LK_{11} + XK_{12}) \\ &-2X(R + r_L)K_{12} - (2r_LR + r_L^2 - X^2)K_{11} = 0 \end{aligned} \tag{11}$$

$$4X(r_L + R)K_{11} - 2(r_LR + r_L^2 - X^2)K_{12} > 0 \tag{12}$$

$$4X(r_L + R)K_{21} - 2(r_LR + r_L^2 - X^2)K_{22} = 0 \tag{13}$$

$$\begin{aligned} &R\left[(2+r_L/R)^2 + (X/R)^2\right](r_LK_{21} + XK_{22}) \\ &-2X(R + r_L)K_{22} - (2r_LR + r_L^2 - X^2)K_{21} > 0 \end{aligned} \tag{14}$$

the parameters K_{11}, K_{12}, K_{21}, and K_{22} defined in equation (15) can satisfy formulas (11), (12), (13), and (14),

$$\begin{aligned} K_{11} &= RX[(2+r_L)^2 + (X/R)^2] - 2X)R + r_L) \\ K_{12} &= 2r_LR + r_L^2 - X^2 - r_L\left[(2+r_L/R)^2 + (X/R)^2\right] \\ K_{21} &= 2r_LR + r_L^2 - X^2 \\ K_{22} &= 2X(R + r_L). \end{aligned} \tag{15}$$

From the analysis above we can see that in fact this is a decoupling control scheme because the proposed control scheme can effectively weaken the coupling between TP_1 (or TP_2) and E_1 (or E_2), and between TQ_1 (or TQ_2) and θ_1 (or θ_2).

3.2 The decoupling control scheme can achieve the active and reactive powers sharing

Although the decoupling control can improve the performance of dynamic response, it is still necessary for the decoupling control scheme to achieve active and reactive powers sharing between the paralleled UPS in static state.

Considering that

$$\begin{pmatrix} TP_1 \\ TQ_1 \end{pmatrix}\begin{pmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{pmatrix}\begin{pmatrix} P_1 \\ Q_1 \end{pmatrix},$$

$$\begin{pmatrix} TP_2 \\ TQ_2 \end{pmatrix}\begin{pmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{pmatrix}\begin{pmatrix} P_2 \\ Q_2 \end{pmatrix}$$

we can see that if the determinant of matrix $K = \begin{pmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{pmatrix}$ is not zero, then $\begin{cases} P_1 = P_2 \\ Q_1 = Q_2 \end{cases}$ can be received from $\begin{cases} TP_1 = TP_2 \\ TQ_1 = TQ_2 \end{cases}$. Obviously the determinant of matrix K is not zero, so the proposed decoupling control scheme can achieve the active and reactive powers sharing in static state.

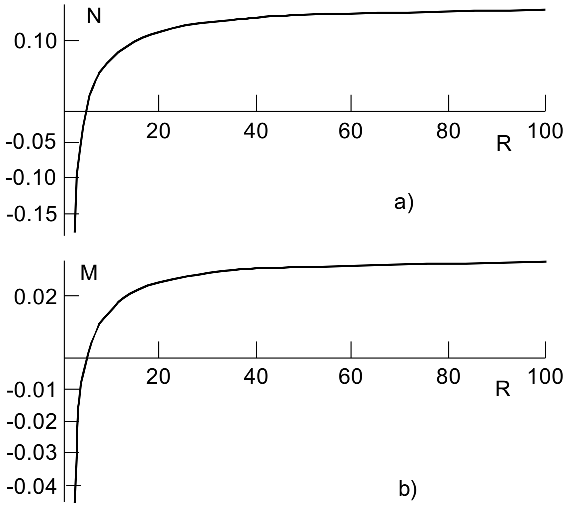

Fig. 2. Curve of M and N vs. R.

3.3 Adaptability of decoupling control to variational load

The analysis above is for the constant load, the following we will analyze the adaptability of decoupling control to variational load. Substituting R_d for R contained in K_{11}, K_{12}, K_{21}, and K_{22}, where R_d is a constant, while R represents the load and may vary as needed, supposing that

$$\begin{aligned} P_1 - P_2 &= M_{11}\big(\sin(\theta_1-\theta_2) + \frac{M_{12}}{M_{11}}(E_1^2 - E_2^2)\big) \\ TP_1 - TP_2 &= M_{22}\big(\sin(\theta_1-\theta_2) + \frac{M_{21}}{M_{22}}(E_1^2 - E_2^2)\big) \end{aligned} \tag{16}$$

$$\begin{aligned} Q_1 - Q_2 &= N_{11}\big((E_1^2 - E_2^2) + \frac{N_{12}}{N_{11}}\sin(\theta_1-\theta_2)\big) \\ TQ_1 - TQ_2 &= N_{22}\big((E_1^2 - E_2^2) + \frac{M_{21}}{M_{22}}\sin(\theta_1-\theta_2)\big) \end{aligned} \tag{17}$$

where M_{11}, M_{12}, M_{21}, M_{22}, N_{11}, N_{12}, N_{21} and M_{22} are parameters related with the paralleled UPS system. Then two variables M and N which represent the adaptability of decoupling control to variational load are defined as equation (18),

$$\begin{aligned} M &= (\frac{M_{21}}{M_{22}})/(\frac{M_{12}}{M_{11}}) = \frac{M_{11}M_{21}}{M_{12}M_{22}} \\ N &= (\frac{N_{21}}{N_{22}})/(\frac{N_{12}}{N_{11}}) = \frac{N_{11}N_{21}}{N_{12}N_{22}} \end{aligned} \tag{18}$$

$M \ll 1$ and $N \ll 1$ states that the decoupling control scheme can effectively weaken the coupling between TP_1 (or TP_2) and E_1 (or E_2), and between TQ_1 (or TQ_2) and θ_1 (or θ_2) comparing with the traditional control scheme. If $R_d = 5\,\Omega$, $r_L = 0.3\,\Omega$, $X = 0.314\,\Omega$, and R varies from $2\,\Omega$ to $100\,\Omega$, the curves of M and N versus R are plotted in Fig. 2. It can be seen from this figure that $M \ll 1$ and $N \ll 1$ are satisfied while R varies from $2\,\Omega$ to $100\,\Omega$. Consequently, the proposed decoupling control can adapt to variation of load.

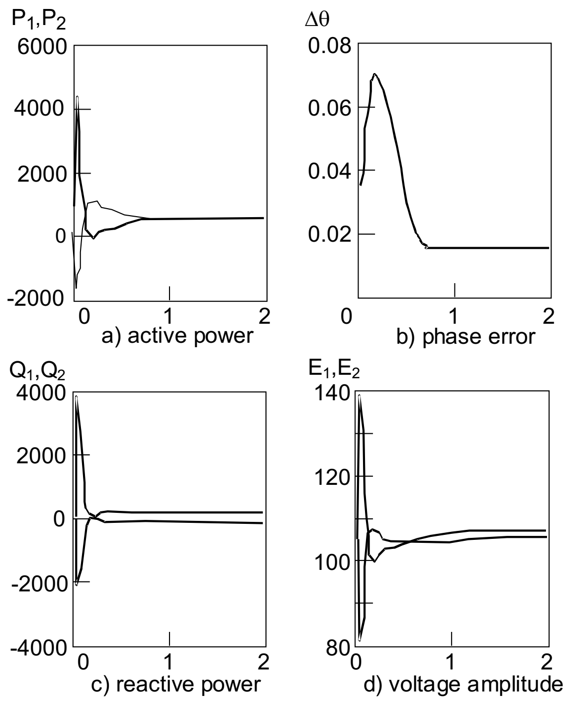

Fig. 3. Simulation waveforms with the control of traditional droop characteristic

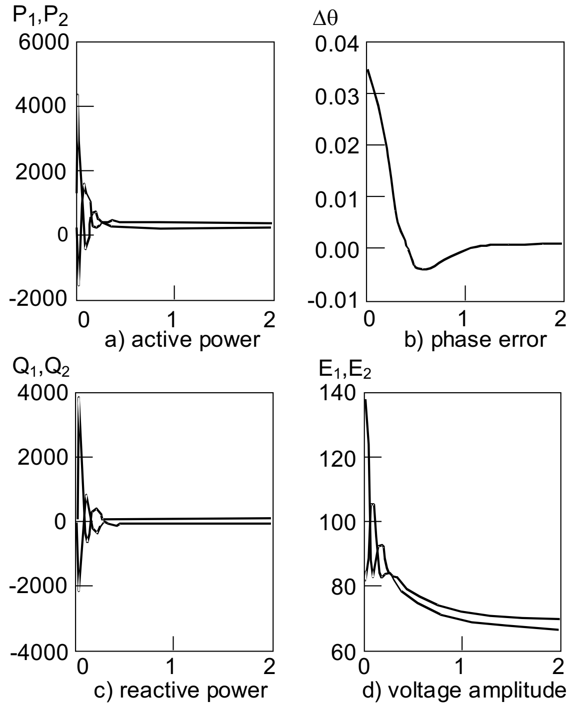

Fig. 4. Simulation waveforms with the control of new droop characteristic

Table 1. System initial parameters

Variable	Value	Unit
E_1	80	V
E_2	140	V
θ_1	2	degree
θ_2	0	degree
X	0.314	Ω
R_d	5	Ω
R	5	Ω

4 THE SIMULATION AND EXPERIMENTAL RESULTS

In order to validate the decoupling control scheme, simulation and experimental results for the parallel operation of two single-phase UPS with no control interconnection are given below. Each UPS is controlled basing on the traditional droop method described in equation (19) and proposed decoupling droop method described in equation (20), respectively.

$$\begin{aligned} f_i &= f_0 - K_P P_i \\ E_i &= E_0 - K_V Q_i \end{aligned} \tag{19}$$

$$\begin{aligned} f_i &= f_0 - K_P TP_i \\ E_i &= E_0 - K_V TQ_i \end{aligned} \tag{20}$$

where $i = 1, 2$, TP_1, TP_2, TQ_1, and TQ_2 are defined as equation (7) and (8).

4.1 Simulation results

Table 1 is the initial condition for simulation, and $K_{11} = 3.34$, $K_{12} = -3.38$, $K_{21} = 2.99$, $K_{22} = 3.33$. Fig. 3 and Fig. 4 show the simulation waveforms with the traditional control scheme and with the proposed decoupling control scheme, respectively.

From the simulation results, we can see the following. Firstly, $P_1 = P_2$ can be achieved with the traditional control scheme, while only $TP_1 = TP_2$ can be achieved with the proposed decoupling control scheme. The reason is that regulating frequency with P_1 and P_2 (TP_1 and TP_2) will lead to $P_1 = P_2$ ($TP_1 = TP_2$) in static state, while regulating the voltage amplitude with Q_1 and Q_2 (TQ_1 and TQ_2) can not achieve $Q_1 = Q_2$ ($TQ_1 = TQ_2$). As a result, in static state $TP_1 = TP_2$ and $TQ_1 \neq TQ_2$ can be obtained under the decoupling control, which will lead to $P_1 \neq P_2$ and $Q_1 \neq Q_2$ in the end. So the decoupling control scheme can not improve the static performance, however, we will see from the following analysis that it can improve the dynamic performance and stability.

Secondly, simulation waveforms show that the voltage amplitude drops sharply, that is because the droop coefficient K_V is very large in the simulation. It can be seen from Fig. 3 that the phase error in static state is near to zero with the proposed decoupling control scheme, but about 0.97° with the traditional control scheme. Considering $E_1 = 105.14$ V and $E_2 = 106.74$ V in static state with traditional control scheme, which can be seen from Fig.3 , the phase error is 0.88° by calculating from equation (5).

Thirdly, the simulation waveforms show that the phase error is enlarged at the starting time and a fixed phase error still exists in static state with the traditional control scheme, while the phase error is decreasing all the time and keeps zero in static state with the proposed decoupling control. We know that $\theta_1 > \theta_2$ but $P_1 < P_2$ is satisfied at $t = 0$. This belongs to the range of positive feedback for the traditional control. As for the proposed decoupling control scheme, the controller can make out that the active power error is caused by the amplitude, but not by the phase, so it controls the voltage amplitude. As a result, the positive feedback does not work, the oscillation and instability can be rejected effectively under the proposed decoupling control scheme.

4.2 Experimental results

In order to validate the proposed decoupling control scheme, we give the experimental results on two paralleled single-phase UPS with no control interconnection. In the experimental, each UPS is controlled with the traditional droop method and with the proposed decoupling droop method, respectively. The parameters for two paralleled UPS are as follows: $R_d = 5\,\Omega$, $r_L = 0.3\,\Omega$, $X = 0.314\,\Omega$, $E_1 = 135$ V, $E_2 = 140$ V, and the load resistance R varies as needed. The two UPS begin to be in parallel operation in the initial situation $\theta_1 > \theta_2$. The waveforms of the output currents, circulating currents, active powers, and reactive powers are shown in Fig. 5 for the instant of paralleling. We can see that the experimental results accord not only with the theoretical analysis but also with the simulation results, at the same time. Fig. 5 shows that oscillation exists with the traditional control scheme while it does not exist with the proposed decoupling control scheme, which states that the stability bas been improved with the proposed control scheme.

5 CONCLUSION

This paper presents a new decoupling control scheme for the parallel operation of UPS, which can overcome the limitation of the traditional control scheme. In order to validate the proposed decoupling control scheme, we give the simulation and experimental results on two single-phase paralleled UPS with no control interconnection. The results of simulation and experiment prove that the proposed decoupling control scheme can effectively reject the oscillation and improve the stability.

Acknowledgement

Project Supported by National Natural Science Foundation of China (50007004).

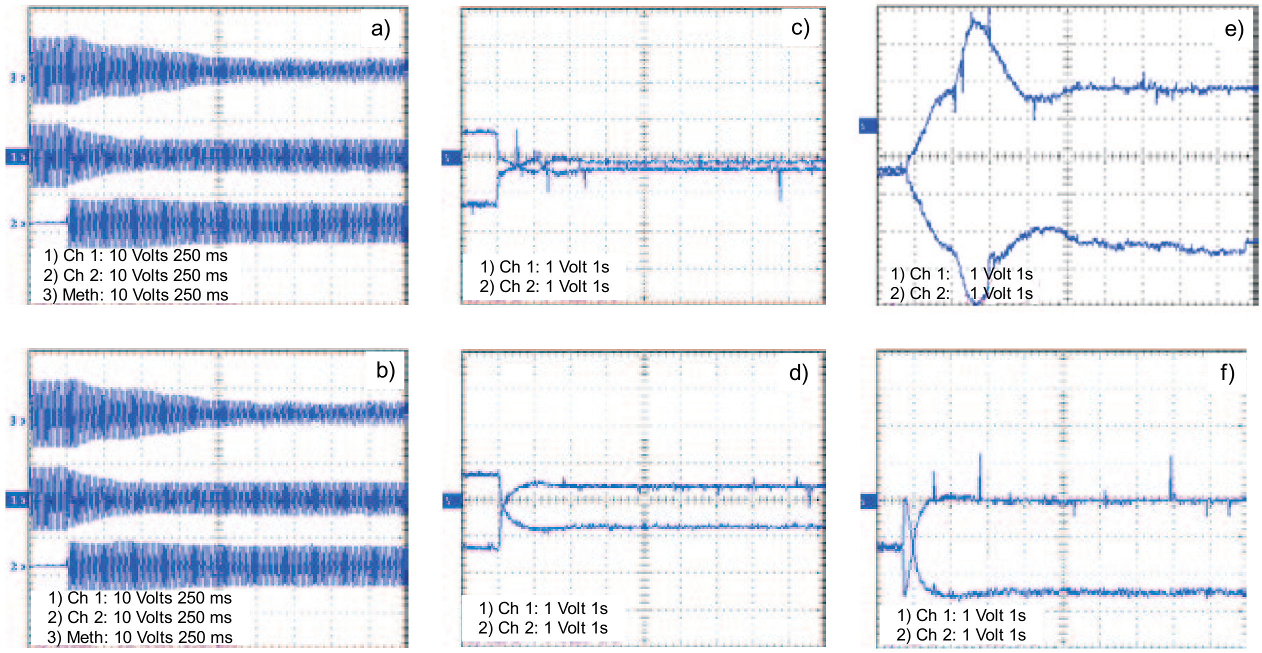

Fig. 5. The dynamic waveforms of current, circulating current, active power, and reactive power at the instant of hot-parallel

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Received 22 November 2002

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